HTS Quasiparticle Injection Devices with large Current Gain at 77 K

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***Abstract*—Recent progress on the development of planar QP-injection devices using YBCO and STO as an epitaxial injection barrier will be discussed. The main problem for HTS injection devices is to grow reliably a well defined, ultra-thin tunneling barrier suitable for QP tunneling. For this purpose, we used inverted cylindrical magnetron sputtering to first optimize the smoothness of our YBCO films by controlling tightly all relevant sputtering conditions. We are able to prepare smooth (001) YBCO films on (001) STO substrates on a routine basis with an average roughness varying between 1 and 2 nm. With these flat YBCO films both planar as well as grain boundary junctions were fabricated using epitaxial STO barriers between 2 and 8 nm thick and a 50 nm of Au counter electrode. Planar junctions with 6 nm STO barriers were in most cases fully insulating, in some cases, a current gain of up to 7.4 at 77 K was obtained. For 3 nm STO barriers, the highest current gain was 15 at 81 K. The injection results also show a scaling behavior with junction size. Based on the present materials development and device understanding, we consider a current gain of up to 20 at 77 K possible.**

I. INTRODUCTION

Three terminal devices based on charge carrier injection in high temperature superconductors (HTS) are potentially interesting as fast devices which could operate in excess of 100 GHz and hence would be a useful addition to already available superconducting applications. Two key requirements are a working temperature of 77 K and sufficient current gain. One hopeful type of device is the injection of spin-polarized charge carriers via a barrier into the superconductor [1,2]. A very high current gain of 35 at 77 K has been reported [1], however, due to the magnetic suppression of the superconducting order parameter and potential heating effects, these devices will be very slow. High frequency measurements for this type of junction have not been reported yet. Over the last few years, there was a continuous improvement in the development and performance of non-equilibrium quasiparticle (QP) injection devices using HTS materials. Progress was twofold. Firstly the current gain improved from about two to more than 15. More importantly, the operation temperature for these fairly high gains is now well above 77 K. These two milestones start to make the injection devices a serious competitor for some applications such as current amplifier, impedance transformer or a fast current switch, e.g. for multplexing, at technically interesting temperatures. In order to achieve these aforementioned goals (high current gain, high operating temperature), a useful epitaxially grown QP tunnel barrier compatible with HTS materials is the essential requirement in order to create a non-equilibrium population of quasiparticles. Several different injection barriers where investigated in the past [3-5], some with a reasonable current gain, others such as $PrBa_2Cu_3O_7$ showed resonant tunneling via 2 localized states and proved to be ineffective as injection barrier. The best epitaxial barrier we can offer at the moment is $SrTiO_3$ (STO) It is a well known and used material as substrate due to the excellent lattice matching to $YBa_2Cu_3O_7$ (YBCO) as well as dielectric barrier for field effect devices.

In this paper we report recent investigations of planar YBCO/STO/Au devices. The current gain of these devices was measured as a function of temperature between T_c and 77 K, and results indicate that a current gain of 20 at 77 K is possible.

II. DEVICE STRUCTURE

For the planar injection geometry experiments reported in this paper, a YBCO/STO/Au structure was used as described in [3]. The thickness of the superconductor varies between 30 and 80 nm and the thickness of the Au electrode is approximately 50 nm with the quasiparticles injected via the STO barrier into a 5 x 20 μm^2 wide YBCO bottom electrode. Due to a large specific resistance of the injector contact ($R_nA > 10^{-5}$ Ωcm^2 for YBCO/Au contacts), the injected quasiparticle flow is uniform over the contact area. In order to insulate the injection electrode and the wiring from the base electrode we used polycrystalline PBCO and SiO_2. All planar devices are patterned using standard optical lithography and ion beam etching.

III. EXPERIMENTAL

The Current-voltage characteristic (IVC) of the superconducting bridge under quasiparticle injection is measured using a four point configuration. Modulating the critical current I_c of the superconductor with the injection current I_G leads to an asymmetry in the IVC which is independent of the direction of the currents. The reasons for the observed asymmetry are twofold: firstly, a summation of

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I_G and I_c called current summation effect and secondly, an additional non-linear suppression of I_c due to a non-equilibrium energy distribution of the injected quasiparticles. The current summation effect yields a linear suppression of I_c with I_G flowing parallel to I_c and no suppression if I_G and I_c flow anti-parallel. A non-linear suppression of I_c with I_G flowing parallel is generally attributed to a non-equilibrium effect due to an excess density of quasiparticles and their non-equilibrium energy distribution. If the non-equilibrium relaxation of quasiparticles is dominant, the asymmetry in the IVC will be less pronounced. For I_c flowing parallel to I_G, I_c cannot be suppressed completely due to the still present current summation effect.

The current and voltage gain for quasiparticle devices is defined as $K_C=\Delta I_c/\Delta I_G$ and $K_V=V_{out}(I_c)/V_G(I_G)$ respectively with the output voltage $V_{out}=\rho J_c L$ in the dissipative state (ρ, the resistivity, J_c, the critical current density and L, the length of the track). In case, the non-equilibrium state can be created by the injected QP, K_C will always be bigger than 1. Pure current summation yields K_C equals 1 ($I_C \propto I_G$), and if the suppression of I_c is linear with I_G and $K_C>1$, heating effects mixed with a non-equilibrium relaxation are the most likely cause for it. The ratio between the effect based on heating and the non-equilibrium relaxation certainly depends on the injected power used. $K_C<1$ can also occur, meaning there is current summation present but also an additional leakage current over the insulation of the top electrode.

IV. Film Preparation

(001) oriented YBCO and (100) oriented STO films were prepared in the same vacuum chamber using dc and rf inverted cylindrical magnetron (ICM) sputtering, respectively. Typical sputtering parameters for YBCO on (100) STO substrates are a deposition temperature T_S of 800 °C, a total pressure of 0.525 mbar with an Ar to O_2 ratio of 1:1 and a dc-power of 45 W. For STO, typical deposition parameters are $T_S = 800$ °C, an Ar to O_2 ratio of 1:1 with a total pressure of 0.05 mbar and a rf power of 75 W. If STO was deposited on YBCO, T_S was reduced to 780 °C in order to stay below the YBCO decomposition line. The sputtering rate for YBCO and STO for the described deposition parameters was regularly monitored using RBS.

With these deposition parameters, T_c for the YBCO films varies between 88 and 89 K with an inductive transition better than 0.5 K. Extensive atomic force microscopy (AFM) investigations of YBCO films showed by controlling the deposition parameters carefully as well as the quality of the substrate surface prior to deposition, smooth YBCO films with no outgrowth and precipitates can be obtained routinely. The average surface roughness is less than 1.5 nm measured over an area of 5x5 μm^2 as shown in Fig.1 compared to about 3 nm in the best case without much control of the sputtering parameters and substrate.

STO was optimized at first using (110) $NdGaO_3$ substrates due to a similar lattice mismatch for STO compared with YBCO. The best films with a total thickness between 20 and 40 nm had a FWHM of the rocking curve at the (200) reflection of better than 0.1° and up to 12 Laue-oscillations were observed indicating a very homogeneous thickness. The measured smoothness of 0.3 nm was comparable to the smoothness of the $NdGaO_3$ substrates. This demonstrates a very well grown film of high crystalline quality.

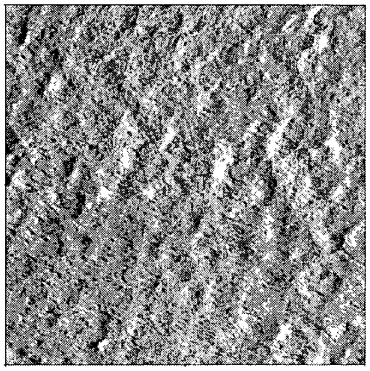

Fig. 1. Smooth surface of a 50 nm YBCO film prepared on STO using ICM magnetron sputtering. The measured average surface roughness is 1.4 nm.

By transferring the optimized STO deposition conditions for $NdGaO_3$ to YBCO, one has to take care about the surface quality of the underlying YBCO film in order to achieve the desired barrier properties. One problem is the natural surface roughness of YBCO, leading to an island growth of STO on YBCO and hence to possible pin-holes in the STO barrier. Adapting the deposition conditions of STO on YBCO, a pin-hole free, 2-3 nm thin STO barrier can be grown successfully as shown is Fig. 2. More details of the materials and barrier properties can be found in [6].

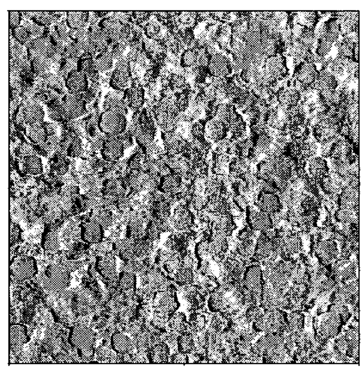

Fig. 2. 3 nm of STO on YBCO with an optimized surface roughness. Some island growth is still present, however, electrical measurements indicate a continuous STO layer

V. Discussion

In the following paragraphs, we would like to discuss some properties of the injection devices as derived from dc-measurements.

A. Barrier Properties

The insulating properties of our optimized STO barriers showing QP injection were characterized by IV-characteristics (IVC). For these measurements, we have deposited a Au-counter electrode onto the YBCO/STO bilayer and patterned 5x20 μm^2 junctions using conventional optical lithography as described elsewhere [3]. A typical IVC of such junctions with a 3 nm STO barrier is shown in Fig. 3.

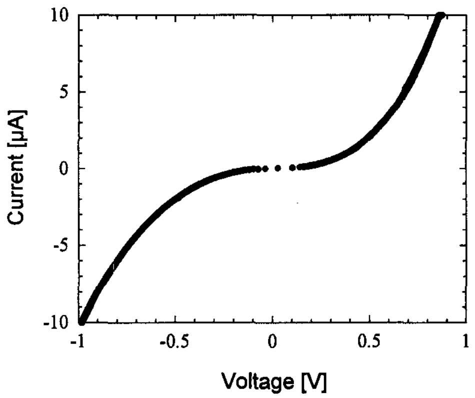

Fig. 3. IV-characteristic of a YBCO/STO/Au junction with a 3 nm STO barrier measured at 4.2 K.

The leakage current for an applied voltage of 0.5 V, corresponding to an electric field strength of 1.7 $MVcm^{-1}$, is only 2 μA. The voltage stability without irreversible breakdown, however, is much better than 0.5 V. A voltage of up to 8 V can be applied without destroying the STO with the consequence of changing the properties or even destroying the underlying YBCO film within minutes. The change of YBCO properties is irreversible and the most likely cause is ion-migration due to the influence of a very large electric field (10^8 V/cm) and an injected current of the order of 100 μA. For 6 nm thick barriers, the resistivity increases to about 2 MΩ with a voltage stability of 10 V and for 10 nm STO barriers, the measured resistivity is bigger than 80 MΩ.

Another interesting feature of this type of barrier is a training effect of the resistivity and the applied voltage. By carefully ramping up and down the injection current, the applied voltage and hence the applied electric field can be increased before the electrical breakthrough occurs as observed for other materials such as PZT [7]. This would indicate the presence of conducting channels in the as-prepared barrier which can be burned out and therefore increase the barrier resistivity and the maximum applied drive voltage for the injected QP.

B. Device Properties

The QP injection into a YBCO track via a STO barrier can be successfully done if the barrier thickness is 6 nm or less or the corresponding nominal thickness depending on the surface roughness of the YBCO film. For some devices with a nominal 6 nm thick barrier, we obtained a best current gain of 7.4 at 77 K as shown in Fig. 4. At 84.6 K, K_C was still 1.9. The origin of the observed large current gain at 77 K is a combination between heating effects as well as a non-equilibrium relaxation.

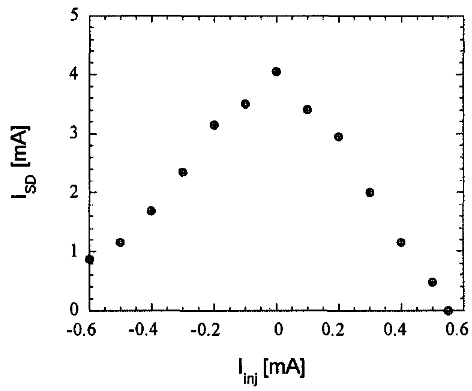

Fig. 4: I_{SD} vs. I_{inj} for an injection device with a 6 nm STO barrier measured at 77 K. K_C is 7.4 and heating effects are expected to be present.

The highest current gain obtained was K_C=15.3 at 81 K using 3 nm thin STO barriers. However, more important are two other facts. Firstly K_C for different junctions was scaling with their length L ($K_C \propto L^{-1}$) and secondly, the injected power for these junctions of about 2000 Wcm^{-2} was clearly smaller than the limit of 3700 Wcm^{-2} [8] where thermal effects start to

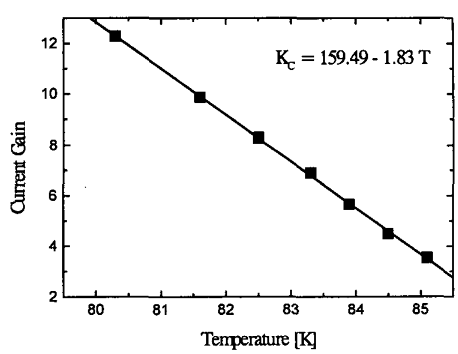

Fig. 5. The measured temperature dependence of the current gain for a YBCO/STO/Au injection device with 3 nm STO barrier.

interfere with the non-equilibrium state. Further, QP tunneling must be present, otherwise the observed magnitude of K_C would be difficult to explain.

As a first approximation, the observed linear temperature dependence of K_C, seems reasonable. Rewriting K_C gives the expression $K_C=J_C\tau_{eff}(\Delta neL)^{-1}$ with τ_{eff} the effective QP relaxation rate, Δn the excess QP density and e, the electric charge. Assuming Δn and τ_{eff} are temperature independent, one would expect an almost linear relationship of K_C with J_C in this temperature regime. However, $\tau_{eff}\propto\exp(1/T)$ between T_c and 50 K, before reaching a saturation value at lower temperatures [9], and $\Delta n\propto\lambda^{-2}\propto(1-T^4)^{-1}$ near T_c [10]. The experimental data suggest, that the counteracting temperature dependencies of Δn and τ_{eff} canceling each other, but at lower temperature one would expect a saturation of K_C as already observed for devices with different injection barriers [4],[5]. In order to know more about the processes involved limiting the effective relaxation time, one would need to measured $\tau_{eff}(T)$ for a real device. However, such measurements have not been attempted yet.

VI. Conclusion

We demonstrated, that STO films of very high crystalline quality and good insulating properties can be prepared on thin YBCO films. The STO film quality can be maintained even if the film thickness is reduced to 3 nm.

For STO films used as QP injection barriers on YBCO, continuous layers between 3 and 6 nm thick were successfully deposited and injection devices prepared. The highest current gain of 15.3 at 81 K was obtained with a 3 nm barrier and better results are expected by decreasing the operating temperature or decreasing the length of the active channel.

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